Dear Santa: Heavy Flavour Physics at Neutrino Factories – Desires from Theory [1]

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Abstract

Even in 2010 the CKM parameters V_{cs}, V_{cd} and V_{ub} will be known with less than desirable accuracy; the discovery potential for New Physics in charm decays – in particular their CP asymmetries – will be far from exhausted; important tests of our theoretical tools will not have been performed. I sketch the impact a νfact could have in these areas.

During this talk I will attempt to sketch which important information on heavy flavour physics will still be missing in 2010. My personal crystal ball tells me that the knowledge base available at that time can be enlargened in three aspects and that neutrino factories (νfact) might be up to the task eventually:

- Some basic SM quantities will be known with less than desirable accuracy.

- The discovery potential in charm decays will be far from exhausted.

Realizing even a single item in these categories through a new initiative would provide a strong motivation for the latter. However to make a conclusive case that some fundamental parameter had indeed been determined more reliably or that the intervention of New Physics had been revealed, one has to make sure that our *theoretical* tools are up to the task:

- The need might still exist to test our theoretical technologies in charm decays.

Obviously one or two measurements are not sufficient to do the job here – a broad and detailed program is called for.

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[1] Talk given at NuFact'00, May 22 - 26, 2000, Monterey, CA

1 Basic Quantities

PDG2000 quotes the following errors on V_{cb} and V_{ub}:

$$|\Delta V_{cb}| \hat{=} 8\% \quad , \quad |\Delta V_{ub}| \hat{=} 40\% \tag{1}$$

For V_{cs} and V_{cd} two set of errors are listed:

$$|\Delta V_{cs}| \hat{=} 17\% \, [2\%] \quad , \quad |\Delta V_{cd}| \hat{=} 20\% \, [3\%] \tag{2}$$

where the first numbers refer to *direct* extractions and the second ones in square brackets reflect what happens upon imposition of three-family unitarity. $|V_{cs}|$ and $|V_{cd}|$ have been studied in semileptonic D decays as well as in neutrino production of charm with the former having more weight in $|V_{cs}|$ and the latter in $|V_{cd}|$.

My expectation is that these uncertainties will be reduced significantly over the next decade, albeit not by an order of magnitude:

$$|\Delta V_{cs}|_{pre-\nu fact} \quad \sim \quad 10\% \, [2\%], \, |\Delta V_{cd}|_{pre-\nu fact} \sim 10\% \, [2\%], \tag{3}$$
$$|\Delta V_{cb}|_{pre-\nu fact} \quad \sim \quad 4\%, \, |\Delta V_{ub}|_{pre-\nu fact} \sim 10 - 15\%, \tag{4}$$

with the quoted uncertainty of 10 - 15 % in $|V_{ub}|$ not being guaranteed [1].

There are strong reasons why we want to reduce these uncertainties further still:

- The CKM parameters are fundamental quantities related to a central mystery of the SM, namely the generation of fermion masses. Many intriguing suggestions have been made to explain these parameters in terms of so-called 'textures' assumed to hold among Yukawa couplings at GUT scales. However even if those texture patterns look completely different at GUT scales, those differences tend to get substantially diminished when running the couplings down to electroweak scales where they can be probed.

- By 2010 various CP asymmetries in B decays should be measured with errors of about very few percent. One pre-requisite for a matching accuracy in the KM prediction is to know CKM parameters to very few percent as well.

A high rate νfact might be harnessed [2] to provide a competitive or even superior determinations of some CKM parameters – as is at present the case with $|V_{cs}|$ and $|V_{cd}|$– through measuring the heavy flavour *production* cross section off the appropriate quarks. Coupling the high statistics with a high quality vertex detector should enable one to measure charm production with an accuracy below 1 %. The problem is to which degree one can predict such a cross section as a function of V_{cs} and V_{cd}. Since one is comparing $d[s] \to c$ with $d[s] \to u$, uncertainties in the parton distribution functions will drop out. The central problem is to which degree of accuracy one can deal quantitatively with the suppression of charm (and ultimately beauty) quark production. A 20 % accuracy in the cross section translating into a 10% accuracy in $V_{cd[s]}$ should be achievable, yet one wants to aim higher.

There are two major theoretical stumbling blocks: (i) The models one has been using to describe the on-set of charm production are of a purely phenomenological nature. The quark mass parameter they contain is not related to the charm mass properly defined in QCD. With the threshold region shaped by non-perturbative dynamics, one needs a nonperturbative definition of the quark mass. While such a definition has been developed for heavy flavour decays [3], this has not happened yet for threshold production. (ii) Uncertainties in the charm fragmentation function constitute a serious limiting factor.

There are two avenues that in combination might lead us towards better theoretical control over charm production: on one hand one can undertake to carry over technologies developed to deal with non-perturbative dynamics in heavy flavour decays to describe heavy flavour production; on the other hand one can analyze to which degree an experiment at such a νfact could measure fragmentation effects with sufficient accuracy to reduce the aforementioned theoretical uncertainties. I would conclude that extracting $|V_{cs}|$ and $|V_{cd}|$ within 10 % should be achievable with the hope that based on further theoretical and experimental work those uncertainties can be significantly reduced. Furthermore the aforementioned complications should basically drop out from the ratio $|V_{cd}/V_{cs}|$.

Less fundamental, yet very instrumental is the extraction of the decay constants f_D and f_{D_s} from $D \to \mu\bar{\nu}$ and $D_s \to \mu\bar{\nu}$, respectively. For comparing the measured value with the one predicted by, say, lattice simulations of QCD would provide an important calibration of that methodology; if it passes, one would be much more confident in its extrapolation to f_B, the analoguous quantity for B mesons. Having a reliable value for the latter, one could then infer $|V_{td}|$ from ΔM_B. Identifying such 1-prong channels by their kink constitutes a formidable challenge. An excellent vertex resolution in a clean environment might provide us with the answer to this challenge.

2   Testing our Theoretical Tools in Charm Decays

The expectation that detectors at a νfact can function like an *electronic bubble chamber* in a clean environment gives rise to the hope that measurements can be performed here that otherwise require a dedicated charm factory.

Very little is known about the *absolute* values of branching ratios for the various charm baryons; the situation for D_s is only somewhat better, and the status for D^+ and D^0 is nothing to brag about, either. With these absolute values representing important engineering input into studies of B decays, they have recently emerged as one of the limiting factors. A high quality detector at a νfact might allow us to infer absolute branching ratios. In the absence of a charm factory the only other method known relies on B decays as source for tagged charm hadrons [6].

The next step would be measuring absolute branching ratios of *inclusive* semileptonic D_s, Λ_c, $\Xi_c^{+,0}$ and Ω_c decays. The $1/m_c$ expansion makes some highly non-trivial

predictions here based on the occurance of sizeable constructive interference effects in the semileptonic widths [4]. Whether $1/m_c$ expansions hold or not is an important issue in its own right and a crucial element in an analysis of $D^0 - \bar{D}^0$ oscillations.

Finally measuring charm transition rates into multi-neutral final states provides us with lessons on quark-hadron duality at the charm scale. It will also help to interprete properly CP asymmetries once they are observed in D decays.

3   Identifying New Physics in Charm Decays

$D^0 - \bar{D}^0$ oscillations are driven by the normalized mass and width differences:

$$x_D \equiv \frac{\Delta M_D}{\Gamma_D} \ , \ \ y_D \equiv \frac{\Delta \Gamma}{2\Gamma_D} \tag{5}$$

I share the usual expectation that while x_D is naturally sensitive to New Physics, y_D is not (except for some contrived scenarios).

The usual folklore is based on two statements: (i) The contributions from the quark box diagrams are highly suppressed and insignificant. (ii) Long distance dynamics yield the leading contributions with x_D, $y_D \sim 10^{-4} - 10^{-3}$. New Physics could naturally enhance x_D to the few percent level. This might be described as the 'King Kong' scenario: one is unlikely to ever encounter King Kong; yet once it happens there can be no doubt that one has come across someting out of the ordinary.

A recent careful SM analysis leads to the following conclusions [5]: The operator product expansion provides a coherent and self-consistent description. The $SU(3)$ suppression of the box contributions described by m_s^4/m_c^4 is untypically strong. Other contributions (given by quark condensates) with GIM factors m_s^2/m_c^2 or even m_s/m_c are numerically leading. There is no need to postulate additional long distance contributions. The numerical estimates, however, change little:

$$x_D \,, \ y_D \ \sim \mathcal{O}(10^{-3}) \tag{6}$$

Studying oscillations requires a flavour tag both in the initial and the final state. So far mainly $D^{*,+} \to D^0 \pi^+$ vs. $D^{*,-} \to \bar{D}^0 \pi^-$ have been used for initial state tagging. A νfact would naturally use the muon of the CC interaction as the initial flavour tag. The final state flavour can be identified by its strangeness or its lepton number: $D^0 \to K^- \pi^+$ or $D^0 \to l^+ X$. Whereas there is no SM background to the latter, there is one to the former, namely the doubly Cabibbo suppressed mode. Studying the time evolution of the decay rate allows one to separate out that component:

$$\Gamma(D^0(t) \to K^+\pi^-) \propto e^{-\Gamma_{D^0}t}\mathrm{tg}^4\theta_C|\hat{\rho}_{K\pi}|^2$$

$$\times \left[1 - \frac{1}{2}\Delta\Gamma_D t + \frac{(\Delta m_D t)^2}{4\mathrm{tg}^4\theta_C|\hat{\rho}_{K\pi}|^2} + \frac{\Delta\Gamma_D t}{2\mathrm{tg}^2\theta_C|\hat{\rho}_{K\pi}|}\mathrm{Re}\left(\frac{p}{q}\frac{\hat{\rho}_{K\pi}}{|\hat{\rho}_{K\pi}|}\right)\right]$$

$$-\frac{\Delta m_D t}{\mathrm{tg}^2\theta_C|\hat{\rho}_{K\pi}|}\mathrm{Im}\left(\frac{p}{q}\frac{\hat{\rho}_{K\pi}}{|\hat{\rho}_{K\pi}|}\right)\right] \ , \quad \mathrm{tg}^2\theta_C\cdot\hat{\rho}_{K\pi}\equiv\frac{T(D^0\to K^+\pi^-)}{T(D^0\to K^-\pi^+)} \tag{7}$$

Another observable is the integrated rate into 'wrong-sign' leptons:

$$r_D\equiv\frac{\mathrm{rate}(D^0\to l^-X)}{\mathrm{rate}(D^0\to l^+X)}\simeq\frac{1}{2}\left(x_D^2+y_D^2\right) \tag{8}$$

Furthermore one can compare the lifetimes determined from different channels, like $D^0\to K^+K^-$ vs. $D^0\to K^-\pi^+$. The experimental landscape can be sketched by the following numbers [6]:

$$|x_D|,\ |y_D|\ \leq 0.028\ ,\ -0.058\leq y_D'\leq 0.01\ ,\ \ 95\%\ \mathrm{C.L.}\ \ \mathrm{CLEO} \tag{9}$$

where $y_D'\equiv y_D\cos\delta_{K\pi}-x_D\sin\delta_{K\pi}$ with $\delta_{K\pi}$ denoting the strong phase shift between $D^0\to K^+\pi^-$ and $D^0\to K^-\pi^+$;

$$y_D=0.0342\pm 0.0139\pm 0.0074\ \ \ FOCUS \tag{10}$$

If FOCUS has seen a genuine signal, then we find ourselves in a conundrum: the value for y_D is an order of magnitude larger than expected – yet it can hardly be attributed to New Physics! While it suggests that ΔM_D is 'just around the corner', it would force us to abandon the 'King Kong' scenario: it makes any claim of New Physics based merely on the observation of oscillations of very dubious validity.

It is expected that the B factories can probe x_D and y_D down to just below 1% [6]. That means that there is a good chance that the question of $D^0-\bar{D}^0$ oscillations has not been fully answered on the experimental level in 2010. It remains to be seen whether a νfact could go down even further by combining different decay channels in the analysis. This involves also issues of systematics. One should probe decays into wrong-sign leptons for the presence of a prompt *non-SM* component through analysing the time evolution in analogy to Eq.(7).

Doubly Cabibbo suppressed (DCS) decays of neutral D mesons are a promising area to search for CP violation. While one pays a heavy price in statistics, the asymmetry can get much larger since it involves the interference between the DCS amplitude and the oscillation amplitude. The time evolution for $\bar{D}^0(t)\to K^-\pi^+$ is obtained from the one for $D^0(t)\to K^+\pi^-$, see Eq.(7), by substituting the analoguous amplitude ratio $\mathrm{tg}^2\theta_C\bar{\rho}_{K\pi}$ for $\mathrm{tg}^2\theta_C\rho_{K\pi}$ and flipping the sign of the last term. This CP asymmetry is controlled by $x_D/\mathrm{tg}^2\theta_C$. If $x_D\simeq\frac{1}{2}\%$ – thus possibly beyond the reach of the beauty factories – one had $x_D/\mathrm{tg}^2\theta_C\simeq 0.1$; i.e., the CP asymmetry could conceivably be as large as up to 10% *without* oscillations having been found through CP insensitive observables $\propto x_D^2$! It is important to analyze how small an asymmetry could be found at a νfact. With a sample size of 10^8 charm hadrons one should reach the 1% level here statistically; yet it is more than a question of statistics. A similar exercise should be done for $D^0(t)\to K^+K^-$. Since the final state is a CP eigenstate, its time evolution is less complex than for the previous

case [2]. In any case, we can be quite confident that any such signal that could be found would reveal the intervention of New Physics – unlike the situation with CP *insensitive* oscillation observables.

The KM ansatz allows for *direct* CP asymmetries to emerge in some Cabibbo suppressed channels plausibly reaching the $\mathcal{O}(10^{-3})$ level. If such an effect were observed on the 0.1% or even 1% level, one would like to decide whether it was still compatible with the KM ansatz or required the intervention of New Physics. An important element in such an analysis would be to reach the required experimental sensitivity in several channels, in particular those that contain neutrals to determine the size and phases of the contributing isospin amplitudes.

4 Summary

The urgency for obtaining answers to some open questions in heavy flavour decays might actually have increased in 2010: (i) With the experimental errors for CP asymmetries in B decays having been decreased to about 2% a matching accuracy in the predicted values will be desirable. (ii) If $D^0 - \bar{D}^0$ oscillations and CP asymmetries in charm decays had been found, one would like to know whether they require New Physics.

It appears possible that a νfact with its novel and even superior systematics could make substantial contributions to these areas: they might allow more sensitive measurements of either the primary effect or of secondary effects that would help us in a proper interpretation of the observations.

References

[1] L. Gibbons, these proceedings.

[2] For more details, see: I.I. Bigi *et al.*, preprint BNL-67404.

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